

## PERFORMANCE CHARACTERISTICS OF PIEZOCOMPOSITE BULK WAVE TRANSDUCERS

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### INTRODUCTION

Piezoelectric ceramic/ polymer composite materials, possessing useful characteristics unobtainable in single phase materials, have been widely investigated over the past ten years. [1]. Their superior matching to low impedance media has been recognized by manufacturers of medical ultrasound and sonar equipment. However, so far as we know, they have received little attention in the field of non-destructive examination. It is evident that they offer superior performance for the inspection of low impedance media; including concrete, wood, fiber reinforced resin composites etc. A review of the types of composite available is presented together with results indicating achievable performance.

### 1:3 COMPOSITE STRUCTURES

The 1:3 composite is the most studied, and practically employed, type of composite. The structure, illustrated schematically in Fig. 1, consists of ceramic posts aligned within a polymer matrix. Typically, the structure is formed by dicing a series of parallel slots in a ceramic blank. These slots are backfilled with low viscosity polymer - typically epoxy. Subsequently, the major surfaces are lapped flat and a common electrode applied over these surfaces. In fact, the electrode may be patterned photolithographically to define individual elements. The structure is sufficiently anisotropic, in terms of elastic and electrical properties, that element definition by electrode alone is adequate. This contrasts with the case where ceramic is used and physical separation of the elements is essential. This type of composite array has been used to great effect by medical transducer manufacturers. An incidental benefit of this approach is that curved arrays may be easily formed by curving the structure while it has been heated to above the glass transition temperature of the polymer. Also, it may be noted that annular arrays are readily feasible since curved elements may be defined with ease photolithographically.

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The acoustic and electrical properties of the composite are controllable over a wide range by judicious design choice of constituent materials and geometry. By varying the ceramic volume fraction, acoustic impedances in the range 8 to 20 MRayl may be obtained with ease. Hence, an optimal match to many of the low impedance media requiring non-destructive evaluation is feasible. Provided that the ceramic post geometry is fine in comparison with the acoustic wavelength, simple modeling techniques are perfectly adequate for predicting the properties of an equivalent homogeneous material [2]. For example, Figs. 2 and 3 illustrate the acoustic impedance and electromechanical coupling coefficient characteristics, respectively, as functions of constituent material properties and ceramic volume fraction. In this case the ceramic is PZT-5A and the polymer is a hard setting epoxy possessing a Young's modulus of elasticity of 6 GPa, a Poisson's ratio of 0.35 and a density of  $1150 \text{ kgm}^{-3}$ . These figures indicate that acoustic impedance is, approximately, a linear function of ceramic volume fraction, while the electromechanical coupling coefficient possesses a value of 0.60 - 0.65 over a wide mid range. However, if the structure is not finely diced, lateral resonant activity may occur between adjacent posts. These resonant modes have been widely investigated and are well understood [3]. Recently, it has been proposed that a distribution of inter pillar dimensions, as opposed to regular dimensions, be used so as to minimize this problem [4]. Finite element analysis is also useful in certain cases [5].

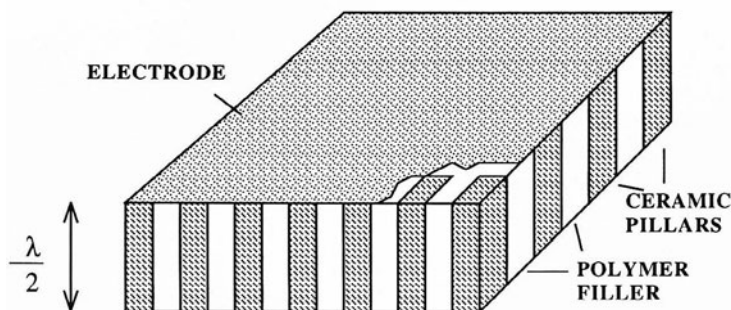


Fig. 1 Configuration of the 1:3 composite transducer

Once a workable composite design has been derived, the parameters of an equivalent homogeneous material may be substituted into a standard thickness mode transducer model so that the practical design, including acoustic and electrical matching, may be tested [6]. Given the diversity of possible designs, it is sensible to test designs using a modeling technique in order to avoid expensive and time-consuming 'trial-and-error' prototype techniques. Typically, one must make a trade-off between a low ceramic volume fraction design possessing low sensitivity and wide bandwidth, and a high ceramic volume fraction possessing higher sensitivity but reduced bandwidth.

As an example, Fig. 4 illustrates the theoretical pulse-echo response obtained from two 20 mm diameter, 2 mm thick transducers operating into a 10 MRayl load. The composite transducer possesses a ceramic volume fraction of 50%. It is assumed that the transducers are air backed. For the sake of simplicity, no matching layer is included. One can see that the composite transducer produces a signal which is far more compact in terms of temporal extent. The peak amplitudes are similar. In an imaging application, the response of the composite would result in a higher resolution 'spot'.

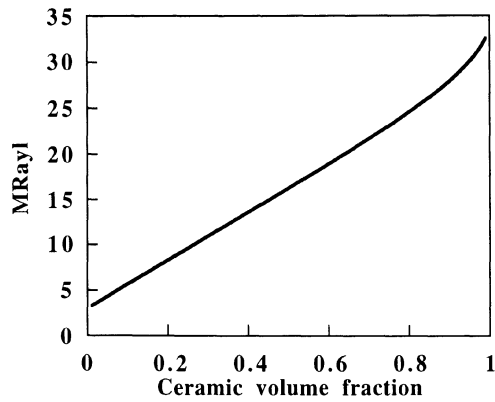


Fig. 2 Acoustic impedance of a 1:3 composite transducer as a function of ceramic volume fraction

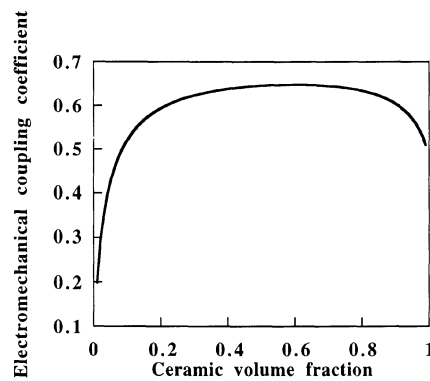


Fig. 3 Thickness mode electromechanical coupling coefficient of a 1:3 composite transducer as a function of ceramic volume fraction

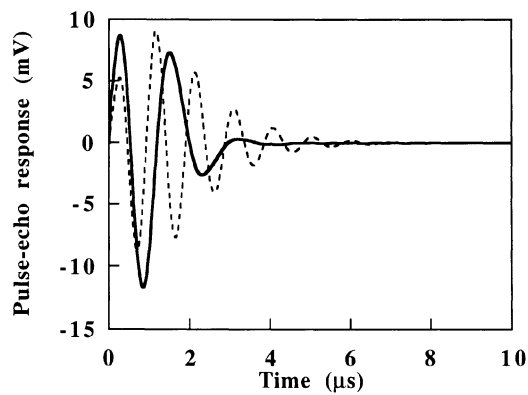


Fig. 4 Modeled pulse-echo performance of airbacked PZT and composite transducers operating directly into a 10 MRayl load.

Composite —————  
PZT - - - - -

Since the composite transducer is well matched to the load, the requirement for a heavy loading is avoided. Hence, by making the composite flexible, it is possible to design a transducer which conforms to curved surfaces. The transducer may be curved permanently by heating, curving and cooling in shape, or, alternatively a flexible polymer may be used in the transducer construction. The versatility of these designs contrasts with the inflexible requirements of conventional ceramic materials which are largely incapable of being molded to conform to complex surfaces and generally require heavy backings in order to achieve good temporal performance.

0.3 COMPOSITE TRANSDUCERS

This configuration comprises of ceramic particles dispersed in a compact, random fashion in a polymer matrix. This structures offers the potential for low cost volume manufacture. However, control of particle size statistics and the nature of the ceramic particle-particle contact require careful consideration and control. At the present time, the theory of the behavior of these materials is incomplete but some manufacturers have been successful in producing small batches of material for sonar applications [7]. Typically, in order to ensure efficient operation, the composite material should possess a ceramic volume fraction of 65%. However, the material is flexible and it offers potential for low cost, large area transducers which conform to curved surfaces. It is therefore suited to the inspection of large concrete structures such as bridges. Unfortunately, the piezoelectric efficiency of existing materials does not exceed that of single phase ceramic. However, there is reason to believe that the properties of these materials may improve if sufficient resources are allocated to research into these structures and to quality-controlled manufacture.

MULTIPLE ACTIVE LAYER TRANSDUCERS

This type of transducer is a composite in a different sense from the two previous designs. Figure 5 illustrates the basic structure. Layer 1 may be controlled as the active component found in any thickness mode operating transducer. However, in this case Layer 2 is added as an 'Active Matching Layer'. The designer may select, within reason, any pair of piezoelectric materials, geometries and electrical excitation/ loading conditions. Hence a considerable diversity of designs are available. The principle advantage of the scheme is that is possible to obtain usable bandwidth continuously from below the fundamental resonant frequency to above the third harmonic [8]. In conventional, single layer designs, a null at the second harmonic is totally unavoidable. The concept of operation, discussed in detail in the literature [8], is to apply a voltage signal to Layer 2 such that the net output response of the transducer is enhanced. As an example, one may apply a signal to Layer 2

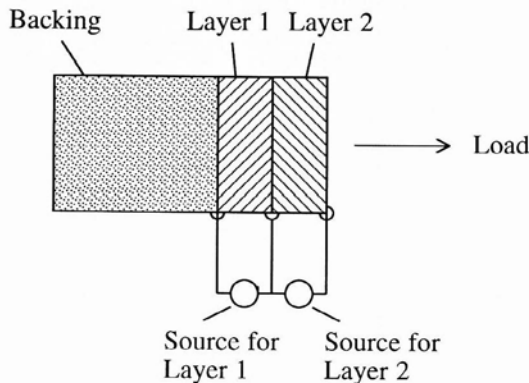


Fig. 5 Configuration of the double active layer transducer

which has the effect of suppressing the ringdown which normally occurs in single active layer transducers. Clearly, the principle disadvantage of the scheme is the added complexity of having to produce signals which are more complex in form than conventional transducer excitation functions.

In an active matching layer transducer configuration, the desired output pressure waveform and the excitation function applied to the primary active layer are predefined. Solving this information to obtain the required voltage excitation for Layer 2 using a circuit analogy model would be tedious. In this case, a Laplace matrix technique, based on one originally described by Lewis [9] is employed. The Laplace transform technique has the important property of converting differential expressions into linear equations using the Laplace operator. A matrix is obtained by assembling constitutive layer equations so that pressure and displacement compatibility is ensured at all boundaries. Lewis considered the case where the force output is unknown and the input voltage is defined. In this case, the output force is defined and hence the matrix problem is rearranged so that a solution for the required voltage across layer 2 is obtained [8].

Since it is not strictly necessary to predefine the excitation of Layer 1, a more efficient use of the multiple active layer mode of operation may be made by solving for the optimal (minimum) excitation for both active layers. The technique employed is briefly reviewed here. It is described in greater detail in the literature [8].

The two layer system, in the Laplace domain, may be expressed as follows:

$$F(s) = A_1(s) V_1(s) + A_2(s) V_2(s) \quad (1)$$

Consider the Mason model for the double active layer transducer illustrated in Fig. 6. It is evident that, using the principle of current superposition from separate voltage sources, the complex value of  $A_1(s)$  may be obtained by letting  $V_1(s) = 1.0$  and  $V_2(s) = 0.0$ . Similarly,  $A_2(s)$  may be obtained by letting  $V_1(s) = 0.0$  and  $V_2(s) = 1.0$ . In order to save space, the Laplace symbol, (s), is dropped in subsequent equations. In the simplest case the layers are of the same material and of the same thickness. Hence, it is desirable to operate the system with  $V_1$  and  $V_2$  equal in terms of magnitude.

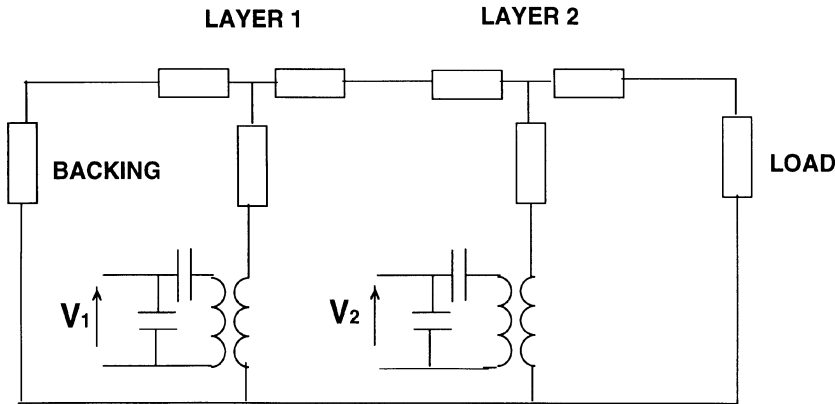


Fig. 6 Mason model of the double active layer transducer

Let  $V_1 = V_2 = 1.0 \angle 0^\circ$  V. Hence, Eq. 1 reduces to:

$$F = A_1 + A_2 \quad (2)$$

or

$$|F| \angle \theta = |A_1| \angle \theta_1 + |A_2| \angle \theta_2 \quad (3)$$

The phasor quantities,  $A_1$  and  $A_2$ , are represented graphically in Fig. 8. Force output,  $|F| \angle \theta$  is maximized if  $\theta_2 = \theta_1$ . In this case  $A_1 V_1$  and  $A_2 V_2$  are in phase and form a straight line when summed. This may be achieved by adjusting the phase angle of  $V_2$  to compensate for the phase difference between  $A_1$  and  $A_2$ . The desired result is obtained by setting  $V_2 = V_1 \angle (\theta_1 - \theta_2)$ . Hence, Eq. 3 becomes:

$$|F_M| \angle \theta_1 = (|A_1| \angle \theta_1)(|V_1| \angle 0^\circ) + (|A_2| \angle \theta_2)(|V_1| \angle (\theta_1 - \theta_2)) \quad (4)$$

$F_M$  is the maximized value of output,  $F$ . It represents the optimized 'transfer function' of the system. Suppose that the desired output is  $|F'| \angle \theta'$ . This is obtained by multiplying Eq. 4 throughout by  $|F'| \angle \theta'$ .

$$|F_M| \angle \theta_1.$$

Equation 4 becomes:

$$|F'| \angle \theta' = \underbrace{(|A_1| \angle \theta_1)(|V_1| \angle 0^\circ)(|F'| \angle \theta')}_{V_1} + \underbrace{(|A_2| \angle \theta_2)(|V_1| \angle (\theta_1 - \theta_2))(|F'| \angle \theta')}_{V_2} \quad (5)$$

Hence, the excitation functions,  $V'_1(t)$  and  $V'_2(t)$  may be obtained using an inverse FFT. Suppose that we wish to produce a  $10^4$  Pa, 1.5 MHz, single cycle pulse using the transducer described in the Appendix. The waveforms to be applied to layers 1 and 2 have been calculated and are illustrated in Fig. 8. In order to test the concepts illustrated here fully, these functions were programmed into a HP 8175A Arbitrary Function Generator and applied to the transducer described in the Appendix. In a practical application, the programmed function would be produced using a low cost circuit composed of a memory IC, a digital counter, a digital to analog converter and an operational amplifier. In this experiment the pressure response was monitored via a novel, very sensitive spot poled ceramic hydrophone [10]. Figure 9 illustrates the measured output observed when the excitation functions illustrated in Fig. 8 were applied to the two layers. The response exhibits the principle features of the desired waveform with some distortion due to diffraction and the influence of an imperfect bond layer.

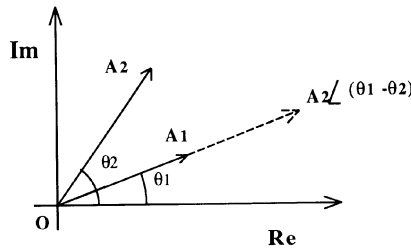


Fig. 7 Phasor diagram illustrating  $A_1$  and  $A_2$ , and the effect of phasing  $A_2$  by multiplying by  $1.0 \angle (\theta_1 - \theta_2)$  and adding to  $A_1$ .

# CONCLUSIONS

Composite transducer designs offer a selection of unique characteristics which make them attractive for use in systems designed for non destructive examination of low impedance media. The increasing use of concrete and fiber reinforced polymer composites, combined with increasing demand for reliable non destructive examination, suggests that piezoelectric composites will be used in these applications. Although piezoelectric composites are generally more expensive than single phase alternatives, transducer material cost is normally small in relation to total system cost. Additionally, composite design and manufacture techniques have been successfully proven in other application areas.

It is also evident that by using multiple active piezoelectric layers substantial improvements in usable bandwidth are available. The mathematical tool employed to determine the optimal excitation functions is simple and proven. Geometry, material properties and electrical excitation may be varied to yield a wide range of characteristics. Furthermore, the practical implementation is relatively simple and low cost.

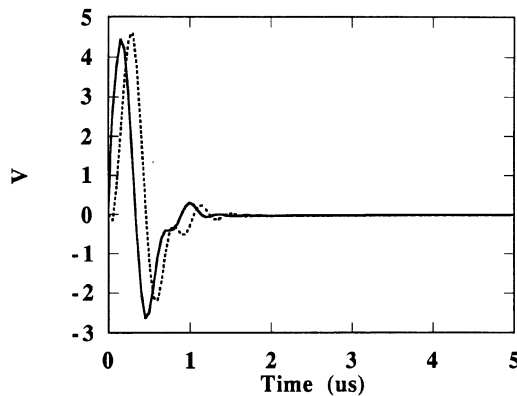


Fig. 8 Modeled voltage stimulation functions required to be applied to Layers 1 and 2, in order to achieve the required output pressure profile.

Layer 1 —————  
Layer 2 - - - - -

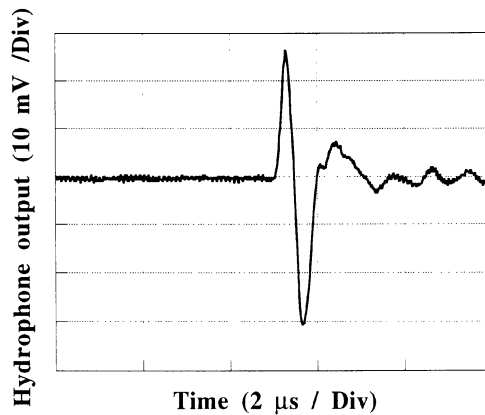


Fig. 9 Experimentally observed waveform obtained when the functions illustrated in Fig. 8 were applied to the double layer transducer

## APPENDIX

### Double Layer Transducer

Diameter:	18 mm
Active Layers:	50% ceramic volume fraction 1:3 composite. Ceramic is similar to PZT-5H
Layer Thickness:	0.5 mm
Backing:	Tungsten loaded epoxy ( 10 MRayl acoustic impedance )

Layers were bonded with a very thin epoxy layer. A thin, protective coat of paint was applied to the front layer.

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